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PS 3: Network planning in the context of an ageing transformer fleet

# Suitability of Ultra High Frequency Partial Discharge Measurement for Quality Assurance and Testing of Power Transformers

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## SUMMARY

Well known reasons for local failures in power transformers are caused by partial discharges (PD) in the electric insulation. Continuous deterioration over time increases the defect which finally can lead to a breakdown of the entire insulation. The importance of PD measurement is accommodated by standardized electrical measurement according to IEC 60270 [1] which is required for acceptance certificates at routine testing. Therefore, the apparent charge Q<sub>IEC</sub> has become an important value for transformer quality. Since a couple of years, alternative measurement methods for PD are used. Originally developed for gas insulated systems [2], [3], ultra high frequency (UHF) measurement found its way into transformer diagnosis over the last years [4]. To become an accepted quality factor, UHF has to be proven a reliable testing method, which can bear up against electrical measurements. Therefore, the general physics of UHF PD has to be considered at first. Ultra-high-frequency antennas measure electromagnetic emissions of PD directly in-oil inside a transformer. It becomes apparent, that UHF measurement usually is advantageous concerning external disturbances. Compared to the electric measurement, the UHF method is robust against external signals [5], which makes it suitable for both, offsite measurement at routine testing under laboratory conditions with low ambient noise and onsite, e.g. after transportation and installation of transformers with usually high noise levels. These considerations make the UHF method interesting as supplement for transformer routine tests. Therefore, a sensor calibration or at least a validation of its sensitivity is required [6] comparable to the electrical measurement. To provide profound knowledge of the equipment, the antenna factor (AF) of the UHF sensor needs to be determined under inside-transformer conditions. This contribution shows the determination of the UHF sensor's AF using a Gigahertz-Transversal-Electro-Magnetic Setup (GTEM cell). To meet inside-transformer conditions, an oil-filled GTEM cell is required for correct permittivity. Correction factors can then be introduced to minimize measurement errors and to establish better comparability of different UHF sensors. Hence, a standard test setup can be defined.

## **KEYWORDS**

Power Transformers, Partial Discharges (PD), UHF PD Measurement for Diagnosis and Monitoring, Routine Testing, Antenna Factor, oil-filled GTEM cell.

# **1 INTRODUCTION**

Power transformers can be considered one of the essential equipment concerning the reliability of the electrical grid. Transformer failures lead to consequential damage with accordant costs. Reliable operation of power transformers is essential for supply security. Damages to the insulation of a power transformer, like local defects, must be recognized at an early stage [7]. Different diagnostic methods have been established to meet the deriving demands for on- and off-site measurements. Electrical PD measurement found its way into standard testing according to IEC 60270 [1]. Within the last decades, alternative measurement methods for PD arise. Originally developed for gas insulated switchgears (GIS) [2] [3], ultra high frequency (UHF: 300 MHz – 3 GHz) PD measurement is also used in power transformers' diagnosis [4], [8], [9]. UHF has been established as a trigger for acoustic PD localization [10], [8], [11] and for onsite/online diagnostic PD measurements [12] and seems to be suitable for on-line PD monitoring [13], [14], [15]. Because UHF measurement is electromagnetically shielded against external disturbances, e.g. corona, by the grounded transformer tank itself, UHF usually is advantageous concerning on-site PD measurements, as seen in Figure 1.



Figure 1 Schematic of Power Transformer with electrical and UHF PD measurement

These features suggest the method for different applications, e.g. comparison of low noise offsite measurement with high noise levels online (after transportation and installation).

Both the measured electrical and the UHF PD levelsare influenced by

- 1. the type and real level of the PD source
- 2. the signal attenuation in the coupling path
- 3. the sensor sensitivity
- 4. the sensitivity of the measurement device.

The influence of the electric "sensor" (coupling capacity and quadrupole) and the measurement device can be corrected using calibration for the electric measurement acc. To IEC 60270. Although the actual PD level can not be estimated [16], [17], [18] because of the unknown signal path attenuation and unknown ratio of internal capacitances, calibration allows the introduction of apparent charge as an acceptance level. Hence, electric measurement is suited for routine tests. Also for the UHF method a correction of sensor influence can be achieved. To determine its sensor sensitivity, the UHF antenna factor (AF) must be known. In previous investigations the AF of UHF sensors was determined within an

air-filled TEM cell in a frequency range up to 950 MHz [19]. It is known that because of different relative permittivity the AF measured in air does not apply to transformer oil, or at least needs to be shifted in frequency range to meet different wave propagation speeds. Furthermore, the full bandwidth of UHF sensors can not be tested with conventional TEM cells. It becomes apparent, that the AF of UHF sensors needs to be determined under inside-transformer conditions at full UHF frequency range. To meet these conditions, an oil-filled Gigahertz-Transversal-Electro-Magnetic Setup (GTEM cell) is required.

## 2 UHF SENSOR CHARACTERISATION

The antenna sensitivity depends on its design and size in relation to the electromagnetic wavelength. Antennas are described by different characteristics, e.g. by the antenna gain or the antenna aperture. For antennas which are not defined by a physical area, such as monopoles or dipoles, the antenna gain is often specified by the effective length  $l_{eff}$  or the antenna factor *AF* which is defined for a receiving antenna as

$$AF(f) = \frac{E(f)}{U(f)} \tag{1}$$

where U(f) is the voltage at the antenna terminals and E(f) is the electric field strength at the antenna [20]. The effective length is defined by the inverse antenna factor. The smaller the antenna factor, the more sensitive is the antenna, because a smaller electrical field strength is needed to receive the same terminal voltage.

For the evaluation of the antenna sensitivity a special setup is necessary with no external disturbances and no internal reflections of electromagnetic waves. Therefore a special equipped EMC absorber room can be used or a GTEM-cell, shown in **Figure 2**. A GTEM cell is an expended coaxial conductor, where a defined electromagnetic field can be applied to an equipment under test (EUT) without interference from the ambient electromagnetic environment.



Figure 2 Schematic of test bed for UHF antennas using a GTEM cell

In the cell a test volume is defined in which measurements take place. In this volume the TEM wave has to be close to ideal, meaning a homogeneous electric field distribution and an orthogonal magnetic field. Also, the electric field strength has to be known. This can be achieved by either measurement using a field probe and/or field simulations.

## **3** TEM CELL TYPES

The transversal electromagnetic mode (TEM) cell [21] was designed based on the concept of an expanded planar transmission line to simulate a free space planar wave for susceptibility testing purposes concerning the electromagnetic compatibility. Beneath the planar inner conductor, called septum, is the usable testing volume in which the planar wave provides a homogeneous electromagnetic field. The equipment under test (EUT), e.g. an antenna, has to be positioned in this defined volume, see Figure **3a/b**.

The frequency domain of conventional TEM cell typically reaches from 0 Hz up into the domain of several 100 MHz, depending on its size and geometry [21]. The frequency range is limited by the cut-off frequency. Above cut-off frequency hollow waveguide resonances can occur and the setup cannot provide one mode of a planar wave. Thus, measurements in the GHz- range need a different setup.



Figure 3 Schematic of a TEM cell. a) plan view b) cross-section

For frequencies exceeding 1 GHz the GTEM cell was developed in 1987 [1].

Compared to the TEM cell the principle geometry of the GTEM cell is a constantly expanding transmission line without a second taper at its end, see Figure **4a**. TEM cells also do not provide an output terminal. The inner conductor is terminated inside the cell with its wave impedance to avoid galvanically coupled reflections. In addition, electromagnetic (EM) absorbers are used as termination for the planar waves. The combination ideally should provide a reflection factor  $r_{termination} = 0$ .

The septum of the GTEM cell is provided by a rectangular transmission line geometry. In comparison to the TEM cell it is not centric to provide a sufficient testing volume for the EUT. Typically, the ratio between septum height and cell height is between 2/3 or 3/4 at any cross-section of the cell, see **Figure 4b**.



Figure 4 Schematic of GTEM cell. a) plan view b) cross-section

## 4 OIL-FILLED GTEM CELL DESIGN

For UHF-antenna measurement the cell's test volume needs to be as large as possible. Therefore, the h/d-ratio is chosen to 0,75. The remaining w/a-ratio is used as variable parameter to adjust the cell's wave impedance.

### 4.1 Wave Impedance

To avoid reflections at both, the input and the termination the entire cell has to operate in 50  $\Omega$  domain. Therefore, its wave impedance *Z* to be adjusted to meet 50  $\Omega$ . *Z* is defined by the perunit-length length parameters given by the equivalent circuit of an infinitesimal short line element: the series inductance *L*', the series resistance *R*' and the conductance *G*' and capacity *C*', both to connected to ground, see equation (2) [22].

$$Z = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}} , \qquad [Z] = \Omega$$
<sup>(2)</sup>

In this setup, both ohmic components R' and G' can be neglected due to the low electrical resistivity of a copper septum and the extremely low conductivity of the oil-filled cell. This leads to the simplified equation (3) for Z.

$$Z = \sqrt{\frac{L'}{C'}} \tag{3}$$

L' and C' has to be estimated for every per-unit-length parameter of the GTEM cell. Both are defined by the line element's cross-section geometry. All parameters are shown in **Figure 5**, where d represents the height of the cross-section, h is the height of the septum in the cell, u is the septum thickness and w its width. If the thickness u is very small compared to the cell height d, u becomes negligible. The simplification is not valid for the inlet of the cell, called apex, if the entire septum is of constant thickness due to production. Therefore, the apex is considered separately from the rest of the septum.



Figure 5 Geometric parameters defining a cross-section of the GTEM cell.

The cell's wave impedance Z can be determined using analytic approximating methods or numeric simulations as field solving algorithms like MOM or FEM.

#### 4.1.1 Analytic Approximation

First, an approximation method for the estimation of the capacitance of a rectangular coaxial transmission line with an infinitely thin and vertically offset septum according to [23] is used. As the applied approximation considers the inner conductor as infinitesimal thin line (u = 0) it is not suited for the apexes impedance estimation.

The capacitance can be calculated using equation (4) were K,  $V_{1n}$ ,  $V_{2n}$  and  $g_n$  are substitutes defined in equations (5) to (8) [23].

$$C = \frac{2\varepsilon_0 \left(1 + \frac{K}{4}\right)^2}{a \sum_{n=1}^{\infty} \left(\frac{1}{w} [V_{1n} + K V_{2n}]\right)^2 g_n}$$
(4)

$$K = -\frac{\sum_{n=1}^{\infty} (4V_{2n} - V_{1n}) V_{1n} g_n}{\sum_{n=1}^{\infty} (4V_{2n} - V_{1n}) V_{2n} g_n}$$
(5)

$$V_{1n} = \frac{4}{n\pi} \sin\left(\frac{n\pi}{2}\right) \sin\left(\frac{n\pi w}{2a}\right) \tag{6}$$

$$V_{2n} = \frac{2w}{a} \sin\left(\frac{n\pi}{2}\right) \left(\frac{\sin\left(\frac{n\pi w}{2a}\right)}{\left(\frac{n\pi w}{2a}\right)^2} + \frac{3}{\left(\frac{n\pi w}{2a}\right)^2} \left[\cos\left(\frac{n\pi w}{2a}\right) - \frac{2\sin\left(\frac{n\pi w}{2a}\right)}{\left(\frac{n\pi w}{2a}\right)^2} + \frac{\sin\left(\frac{n\pi w}{4a}\right)^2}{\left(\frac{n\pi w}{4a}\right)^2}\right]\right)$$
(7)  
$$g_n = \frac{a}{\varepsilon_r n\pi \left(\coth\left[\frac{n\pi h}{a}\right] + \coth\left[\frac{n\pi (d-h)}{a}\right]\right)}$$
(8)

The speed of light in a medium or the phase velocity 
$$v_{phase}$$
 of the lossless transmission line is defined by the angular frequency  $\omega$  and the according phase coefficient  $\beta_{lossless}$  (9).

$$c_{medium} = v_{phase} = \frac{\omega}{\beta} \qquad \beta_{lossless} = \omega \sqrt{L'C'}$$
 (9)

With the provided capacity *C*' of the line segment its characteristic impedance *Z* can be calculated. By solving the system of equations given by (3) and (9) *Z* can be defined either using the speed of light in the oil-filled cell  $c_{medium}$  or by the speed of light in vacuum  $c_{vacuum}$  and typical permeability  $\varepsilon_r = 2.2$  of the oil (10). For all following considerations oil is assumed as a non-dispersive medium, meaning the permeability is used as a constant independent of the frequency. Hence, group velocity and phase velocity are equal [24].

$$Z = \frac{1}{c_{medium}C} = \frac{\sqrt{\varepsilon_r}}{c_{vacuum}C}$$
(10)

**Figure 6a** shows the calculated impedance Z depending on the septum width to cell width ratio (w/a-ratio) at three different heights of the septum and **Figure 6b** shows the characteristic impedance Z as function of h/d at constant w/a. As Figure 6 indicates, the line impedance can be kept constant at any chosen cross-section if the geometric properties of the cross-section cell along the cell's elevation remain constant.



Figure 6 Line impedance Z of the oil filled GTEM cell at

a) 3 different septum height to cell height (h/d) ratios and varying septum width to cell width ratio (w/a)

b) 3 different septum width to cell width ratios (w/a) and varying septum height to cell height (h/d) ratio

For the oil-filled GTEM-cell with fix h/d-ratio = 0.75 (Figure 6a, green line) the septum has to be designed to meet a w/a-ratio of approx. w/a = 0.4. For a given septum size and impedance matching (Z = 50  $\Omega$ ) Figure 6b can be used for cell design).

### 4.1.2 Numerical Model

Beside the analytic model a numeric model solved by a finite element method field solver is used to calculate the wave impedance of the oil filled GTEM cell. Since the cross-section and thus the cell's wave impedance is independent of the length, it is sufficient to perform a 2D simulation for the electric and magnetic field distribution of the cross-sections, as shown in Figure **8b**. Using the resulting simulated electric and magnetic field energy the capacitance C' and inductance L can be calculated by equations (11) and (12).

$$W'_{el.} = \frac{1}{2} C' \hat{u}^2$$
 (11)

$$W'_{magn.} = \frac{1}{2} L' \hat{\imath}^2$$
 (12)

Assuming a lossless septum, the wave impedance is calculated according equation (3). Figure **8a** shows the simulated dependency between wave impedance and w/a-ratio at three different cross-sections from Figure **7** which only differ in the u/d-ratio. Its influence is a parallel translation of the impedance curve with falling impedances at higher u/d-ratios.

The numerical solution and the analytical approach can be compared at cross-sections where u/d is small. Cross-sections 2 and 3 comply with this condition as can be seen in Figure 8a. The simulation at cross-sections 2 exactly matches the analytic result; cross-section 3 shows little deviation due to the similar u/d-ratios.

### 4.2 Septum geometry

Because FEM takes the septum thickness into account, the numerical model is used for cell dimensioning. At a constant h/d-ratio for sufficient testing volume size and also constant septum thickness u due to producibility reasons the w/a-ratio is the remaining variable which has to be optimized along the cell.



Figure 7 Change of u/d and w/a-ratios over GTEM cell length in z direction

Therefore, the three cross-sections shown in **Figure 7** represent the nodes along the GTEM cell length *l*. According to Figure **8a** the *w/a*-ratio at cross-section 1 is 0,369 and 0,395 respectively 0,4 for the others to meet 50  $\Omega$ .



Figure 8 a) Calculated wave impedance Z for cross-sections depending on the *w/a* ratiob) FEM-simulated magnetic and electric field in a cross-section of the GTEM cell

Because the changes of the w/a-ratio along the cell direction are small, a linear fitting function is chosen which eases septum manufacturing. The fit given by equation (13) yields a tolerable error of the wave impedance, see below.

$$\frac{w}{a}(l) = \frac{0,000028}{mm} \cdot l(mm) + 0.3662 \qquad l = [100mm..1312mm] \tag{13}$$

The absolute septum width w(l) is defined by the cell width *a* at cross-section 1. To fulfil the requirement of sufficient testing volume, *a* is set to 68 mm at l = 100mm. Hence, w(l) is defined as:

$$w(l) = 0.213 \cdot l(mm) + 3.8539mm \quad l = [100mm..1312mm] \tag{14}$$

Figure **9a** shows the resulting *w/a*-ratio in the range from l = [100mm..1312mm]. The plot is obviously nonlinear but logarithmic. Nevertheless, the error made in the resulting wave impedance is very small as Figure **9b** illustrates. The absolute maximum deviation is at the cell's end with 0,06  $\Omega$  or 2 ‰.



Figure 9 Influence of the septum geometry on the impedance

a) septum ratio w/a over length from 100 mm to 1300 mm.

b) resulting impedance along the cell length

The small error in the septum's calculated wave impedance is considered negligible and will probably be exceeded by manufacturing tolerances.

## 4.3 Apex geometry

The inlet where the septum is connected to the coaxial cable, called apex, has to be treaded separately because its h/d-ratio cannot be kept constant. The connector to the external attached coaxial cable demands an inner conductor at an h/d-ratio of 0.5. Hence, the first 100 mm of the septum has to adjust the ratio to 0.75 by keeping the 50  $\Omega$  condition. For easy manufacturing, the height adjustment is linear over the apex's length. Additionally, the septum thickness u has a significant influence due to the small absolute height d of the cell. The resulting apex shape needs to address all three issues.

Therefore, the apex is divided into 5 cross-sections at equidistant distances. FEM simulation for each section is optimized to meet 50  $\Omega$  by iterative adjustments. The cross-section at l = 100 mm is optimized to meet the impedance of the septum geometry calculated in the previous chapter. The result is fitted using a forth order polynomial. Accordingly, equation (15) defines the apex width  $w_a$  along the cell's length l.

$$w_{a}(l) = -\frac{1.79 * 10^{-8}}{mm^{3}} * l^{4} - \frac{4.934 * 10^{-6}}{mm^{2}} * l^{3} - \frac{2.048 * 10^{-4}}{mm} * l^{2} + 0.276 * l + 6.309 \text{mm}$$

$$l = [0mm..100mm]$$
(15)

Figure **10a** shows the corresponding *w/a*-ratio of the apex and Figure **10b** the resulting wave impedance. The absolute maximum deviation from 50  $\Omega$  by chance the same as for the rest of the septum 0,06  $\Omega$  or 2 ‰.



Figure 10 a) optimized w/a ratio at constant apex thickness u b) resulting apex impedance over length from 0 mm to 100 mm

# 4.4 Termination

To avoid reflections at the cell's end the galvanic termination of the septum has to be 50  $\Omega$ . In this case an area resistance over the whole septum width is used. It consists of small surface mounted ohmic resistances connected in parallel on a printed circuit board (PCB). For this purpose, resistances with small line inductivity and stray conductivity are used. To provide the desired area resistance effect, the concentrated elements are positioned close to each other. Their distances must be smaller than  $\lambda/10$  of the minimum wave length at maximum frequency (1 mm for 3 GHz) to avoid reflections.

Despite the galvanic termination, also the energy of the electromagnetic waves demands consideration. Conventional EM absorbers and ferrite plates are suited for attenuating EM waves in the GHz range and are attached at the cell's termination wall. The oil-durability of the absorber material has to be ensured.

# 4.5 Wave Impedance over GTEM cell

The overall resulting wave impedance along the cells geometry is shown in Figure **11**. From 0 to 100 mm the apex geometry is used to compensate the influence of the apex thickness and the adoption of the height ratio. At 100 mm is the continuous but not differentiable interconnection between apex and septum geometry. The influence of the termination is not yet considered.



Figure 11 Impedance of GTEM cell along cell length

## 4 CONCLUSION

Electrical and UHF measurement are influenced by the actual level of the PD source, the signal attenuation in the coupling path, the sensor sensitivity and the sensitivity of the measurement device. Because electric measurement equipment (coupling capacitors and quadrupole) can be calibrated it is suited for routine tests. To become a comparable method, also UHF needs standardization of its measurement equipment: UHF antennas require calibration or at least a validation of their sensitivity. Therefore, the antenna factor needs to be determined under reproducible conditions which also meet inside-transformer conditions in the UHF frequency range (300 MHz – 3 GHz). To consider the radio frequency properties of the insulation inside transformers an oil-filled GTEM cell is designed to meet 50 Ohm conditions for measurement purposes. The cell provides a test volume with known electric and magnetic field strength and far-field conditions using the TEM mode. The dimension must be chosen according existing typical antenna sizes and geometries. Using this setup, the antenna factor of any UHF sensor can be determined as implemented in the transformer's inside to characterize the sensor. Hence, a statement of the sensor quality and its performance in comparison can be made. The test setup has to be compatible for various systems like drain valve mounted sensors and top hatch or plate sensors which are integrated directly into transformer tank walls.

A standard setup like the presented approach provides comparability of different UHF sensors and can therefore be valuable for the UHF measurement to become an accepted method for transformer diagnostics and monitoring.

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